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Active sitting with backrest support: Is it feasible?

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Active sitting with backrest support: Is it feasible?

Abstract: Ergonomics science recommends office chairs that promote active sitting to reduce sitting related complaints. Since current office chairs do not fulfil this recommendation, a new chair was developed by inverting an existing dynamic chair principle. This study compares active sitting on the inverted chair during a simulated computer based office task to two existing dynamic office chairs (n=8). Upper body stability was analysed using Friedman ANOVA ($p=.01$). Additionally, participants completed a questionnaire to rate their comfort and activity after half a working day.

The inverted chair allowed the participants to perform a substantial range of lateral spine flexion (11.5°) with the most stable upper body posture ($\leq 11\text{ mm}$, $\leq 2^\circ$, $p \leq 0.01$). The results of this study suggest that the inverted chair supports active sitting with backrest support during computer based office work. However, according to comfort and activity ratings, results should be verified in a future field study with 24 participants.

Keywords: active sitting, ergonomic office chair, motion axis, office ergonomics, back pain

Practitioner Summary: This experimental laboratory study analyses the feasibility of active sitting with a backrest support during common office work on a new type of dynamic office chair. The results demonstrate that active sitting with a backrest support is feasible on the new but limited on existing chairs.

Word count: 4531

Twitter: A new type of dynamic office chair with its unique seat motion promotes active sitting with backrest support. @ZHAW

1 Introduction

Western people spend the majority of their daily life in a seated position (Chau et al. 2013). The movement of the body is thereby restricted by the seat surface, the backrest, and in the case of computer work, the desk. These external constraints, together with office task demands, limit the variability of the sitting posture and lead to specific burdens on the musculoskeletal system. However, there is controversial evidence whether prolonged sitting in general causes low back pain (LBP) (Lis et al. 2007; Ortiz-Hernández et al. 2003; Pope, Goh, and Magnusson 2002; Spyropoulos et al. 2007). In fact, office workers quite often report work related musculoskeletal symptoms in the lower back, with reported prevalence ranging from 22% (last 4 month) to 34% (last 12 months) up to 42% (last 1 week) and 55% (last 4 weeks) (Daneshmandi et al. 2017; Janwantanakul et al. 2008; Janwantanakul et al. 2011; Juul-Kristensen et al. 2004; Spyropoulos et al. 2007).

To maintain an upright sitting posture, a constant isometric muscular effort is needed (Curran et al. 2015; Vergara and Page 2002). Near-infrared spectroscopy shows that tissue oxygenation in lumbar musculature is reduced as a function of muscular contraction intensity (McGill, Hughson, and Parks 2000). A reduced tissue oxygenation is observed even at levels as low as 2% of maximum voluntary contraction. To reduce oxygen deficiency in the postural muscles, prolonged static sitting should be interspersed with periods of active sitting. In fact, static working postures lead to muscular fatigue much faster than dynamic ones (Carter and Banister 1994) and the recovery time of statically loaded muscles is longer than the holding time (Corlett 2006). Furthermore, LBP is hypothesized to be prevalent among office workers due to monotonous low-level mechanical loads on the spine and other joint tissues while sitting (van Dieën, de Looze, and Hermans 2001), as well as the accumulation of

metabolites in the intervertebral discs (Pope, Goh, and Magnusson 2002). Both of which can be counteracted by continuous movements while sitting (Corlett 2006), referred to as active sitting. Thus, ergonomists recommend active sitting during working hours. However, no dynamic office chair has been found that significantly increases physical activity and thus changes the trunk muscle activity (Ellegast et al. 2012, O'Sullivan et al. 2013). Despite presumptions, Grooten et al. (2013) found that the postural sway is lower when sitting on an advanced dynamic office chair (ADV), compared to a conventional dynamic office chair (CONV). However, even CONVs are not used in an active manner (Ellegast, Keller, and Hamburger 2008; Ellegast et al. 2012; Grooten et al. 2013; Jensen and Bendix 1992; van Dieën, de Looze, and Hermans 2001).

The largest body motions while sitting on CONVs typically occur in the sagittal plane (Ellegast, Keller, and Hamburger 2008), characterized by a significant anterior-posterior head motion, and thus, a change in the field of view (van Dieën, de Looze, and Hermans 2001). The sagittal plane motion is therefore not suitable for active sitting with continuous body motion during focused office work. In addition, the motion in the sagittal plane merely means that the hip flexion angle and the orientation of the spine as a whole are changed. The chair mechanic does not support a flexion-extension movement of the spine.

The seat motion in the horizontal plane (the second degree of freedom of CONVs) is characterized by a twisting about the longitudinal axis of the spine if the head remains in the same position. The higher level of muscular activity needed to twist the spine increases the intradiscal pressures, which may explain the relationship between twisting and LBP (Pope, Goh, and Magnusson 2002). Nevertheless, van Deursen et al. (1999) and Lengsfeld et al. (2000 and 2007) investigated an office chair allowing such a horizontal motor-driven rotation with a frequency of either 0.2 or 0.08

Hz and a range of motion (ROM) of either 0.8° or 1.8° to each side. Although they found a positive short-term influence on the reduction of LBP (van Deursen et al. 1999), a long-term comparison failed to show any benefits compared with CONVs (Lengsfeld et al. 2007).

To promote active sitting while completing computer-based work, maintaining a stable upright position of the thorax and head is assumed to be key in order to focus on the computer screen and to manipulate the keyboard and mouse (Bush and Hubbard 2008; Kuster et al. 2016; van Dieën, de Looze, and Hermans 2001). In addition, the absence of a stable upper body posture is hypothesised to result in a reduced work performance (Grooten et al. 2017). Only a stable upper body position allows the office worker to use the support of the backrest and to relax their back muscles (Curran et al. 2015). However, in order to promote active sitting, the subject should be able to move their body in a considerable ROM. It was hypothesized that the solution to these conflicting demands is to invert the dynamic principle of ADV (having a motion centre for the seat below the seat level, as investigated by e.g. Grooten et al. 2013 and O'Sullivan et al. 2012) and add it to a CONV. By inverting the principle, the motion centre is located above the seat level within the chair user's body (inverted dynamic office chair, INV). In this way, the user should be able to flex their spine laterally, while the thorax and head maintain a vertical position in order to use the support of the backrest (Figure 1 and 2). To benefit from the backrest, the additional degree of freedom of INV was limited to the frontal plane.

A first study about INV optimized the location of the motion axis above the seat level (Kuster et al. 2016). This second study analysed and compared the feasibility of active sitting with backrest support for INV, ADV, and CONV (Figure 2). For this purpose, the kinematic motion pattern of the upper body while active sitting was

analysed in an office-like laboratory setting. Additionally, to compare the two principles with frontal plane motion (INV and ADV), comfort and activity ratings gathered after half a working day were analysed.

[Insert Figure 1 near here]

2 Methods

2.1 Participants

Based on the sample size calculation (Section 2.2), a total of 8 self-reported pain-free students were recruited. Participants were included if they met the following criteria: sit daily for at least four working hours, be familiar with any kind of CONV, and have no known musculoskeletal or neurological diseases or previous back operations. The mean age and standard deviation of all participants (4 men and 4 women) was 27.1 ± 3.6 years, mean body height 172.8 ± 4.7 cm, and mean body weight 61.5 ± 1.9 kg. No participant was familiar with INV and ADV prior to data collection. A regional ethics board approved the study, and all participants gave their written consent prior to data collection.

2.2 Outcome Measures and Sample Size Calculation

The primary aim of this study is to analyse the impact of the motion axis location on upper body kinematics and to study the feasibility of active sitting with backrest support. Primary outcome measures are lateral motion of the body segment head, thorax, spine and pelvis. It was hypothesized that translations of all body segments, as well as inclination of thorax and head, are significantly reduced for INV (to enable the backrest support), while lateral spine flexion and pelvis inclination are not affected by motion axis location (to enable active sitting). A stable upright position of the thorax and head are considered to be the most crucial condition for promoting active sitting during computer based office work, while not affecting work performance (Bush and Hubbard 2008; Grooten et al. 2017; van Dieën, de Looze, and Hermans 2001). Thorax and head inclination was consequently used for sample size calculation, with $\alpha=0.01$ and an expected difference of $2.0 \pm 0.8^\circ$ that was considered to be relevant for

office work with respect to previous findings (Ellegast et al. 2012, Grooten et al. 2013), leading to $n=8$ (Faul et al. 2007).

Secondary outcome measures were subjective chair ratings regarding comfort and activity for the two chairs having the additional frontal-plane degree of freedom (INV and ADV). Data were used to verify whether the chair rating reflects the findings of the kinematic analysis and to calculate the required sample size for a subsequent field study.

2.3 Dynamic Office Chairs

The chair according to the inverted dynamic principle (INV) was constructed by rotavis[®] (Winterthur, Switzerland) for this study. rotavis[®] equipped a CONV with an additional motion axis above the seat level as described in Kuster et al. (2016). Accordingly, the seat of INV can be moved in the frontal plane in a convex manner around an antero-posterior axis (Figure 2).

The chair according to the advanced dynamic principle (ADV, model Swopper from aeris[®], Munich, Germany) is equipped with an additional motion axis below the seat level. Accordingly, the seat of ADV can be moved in the frontal plane in a concave manner (Figure 2).

The seat of the chair according to the conventional dynamic principle (CONV, model Verona from topstar[®], Langenneufnach, Germany) is not equipped with an additional frontal plane motion axis, representing the most popular dynamic office chairs. Accordingly, the seat of CONV was not moveable in the frontal plane (Figure 2).

Note that INV and CONV differ only in the additional motion axis of INV. All seats were additionally moveable in the sagittal and horizontal planes.

[Insert Figure 2 near here]

2.4 Procedure

Prior to the kinematic measurements, participants sat for half of a working day on INV and ADV to familiarise themselves with the unique seat motions. Participants were asked to perform their usual computer work without any restrictions. The chair order was randomized. After half of the working day, participants rated the chair with a questionnaire while sitting on it.

For the subsequent kinematic measurements, participants were asked to sit actively as they did during the familiarisation period while performing a simulated computer based reading task. For this, a hologram was placed on the desk in a distance of 80 cm. Participants were asked to fix the hologram in their field of view so that the image does not change. This set-up allowed the participants to move the head up to a maximum of 5 cm in lateral direction. This task was selected because computer work is known to be the least active office task, and there are no known differences between different computer tasks (Groenesteijn et al. 2012). Since CONV was not included in the familiarisation period (familiarity with CONV used as an inclusion criteria), participants were asked to perform the same lateral flexion of the spine as on INV and ADV. For every participant, 3 recordings were made for each chair (in randomized order), and each recording consisted of 6 movements to both sides. The recordings for each chair took approximately 3 to 5 minutes. To ensure visibility of the markers on the thorax, spine and the pelvis, measurements were performed without a backrest. Note that, although performed after the half working day, the kinematic results are reported first because they answer the primary question of this study.

2.5 Data Collection

An optoelectronic motion capture system was used for kinematic data collection (Vicon MX system, Oxford Metrics Group[®], Oxford, UK). Seven infrared cameras

recorded the positions of the markers that were fixed at bony landmarks on the skin of the participants according to the Plug-in-Gait-Model (Davis et al. 1991; Kadaba, Ramakrishnan, and Wootten 1990), with additional markers on the spine and the pelvis (Ernst et al. 2013, Table 1). The recording frequency was set to 200Hz. Subsequent three-dimensional marker reconstruction was done using Vicon Nexus 1.5.2 (Oxford Metrics Group®).

Participants rated the chairs after the half working day using a written questionnaire (Appendix). The questionnaire is based on the study of Groenesteijn et al. (2012). Response options were given in a six point anchored Likert scale.

[Insert Table 1 near here]

2.6 Data Analysis and Statistics

All calculations and statistical tests were performed using MATLAB 2013a (MathWorks Inc.®, Massachusetts, USA). To analyse the range of lateral translation of each body segment, the midpoint of all markers belonging to a segment was computed (Table 1). ROM was then obtained by calculating the difference between the two extremal positions (left and right). For the pelvis, the midpoint was shifted caudally (perpendicular to the upper pelvis edge) by half the pelvis height, since all markers were attached to the upper pelvis edge. Lateral spine translation was obtained in the same manner, but on an individual marker level.

The angular motions in the frontal plane of the segments head, thorax, and pelvis were determined by calculating the Euler angles and likewise obtained at the two extremal positions. For the lateral flexion of the spine, the angular difference between the lowermost (L5 to L3) and uppermost spinal segment (T2 to C7) was calculated.

Finally, in order to express the ROM of a unidirectional body motion, all results were halved and compared by applying a Friedman ANOVA since Lilliefors test

rejected the normal distribution. If differences at the level of $p=0.01$ were detected, the chairs were individually compared using a post-hoc Wilcoxon matched-pair test.

Responses to the questionnaire were numbered from 1 (worst) to 6 (best) and compared on a global and single question level using a Wilcoxon matched-pair test. The level of significance was again set to $p=0.01$. Since the study size was determined for the kinematic analysis and chair ratings were gathered for an explorative analysis, effect sizes (ES) according to Cohen (1988, 1992) were calculated to detect statistical trends. A statistical trend was defined as $p \leq 0.1$ with $ES \geq 0.8$ and indicates a high probability for large differences between the chairs. If such a trend was found, the sample size for which the trend would become significant was determined according to Faul et al. (2007) to inform a future field study.

3 Results

3.1 Primary Outcomes

Active sitting on INV resulted in a significantly reduced lateral head and thorax inclination, as well as thorax translation (Figure 3). Although the average head translation was also the smallest, the difference was not statistically significant ($p_{\text{Friedman}}=0.14$). No difference was found for the lateral spine flexion ($p_{\text{Friedman}}=0.07$). The lateral pelvis inclination showed a difference among the global ($p_{\text{Friedman}} \leq 0.01$), but not on an individual level ($p_{\text{Wilcoxon}} \geq 0.02$). For INV, no pelvis translation was noticed on average, while ADV showed the significantly highest pelvis translation ($p_{\text{Wilcoxon}} \leq 0.001$).

The lateral spine translation showed a significant overall effect of motion axis location for the lumbar and lower thoracic spine (from L5 to T10), whereas the translation for INV was the smallest ($p_{\text{Wilcoxon}} \leq 0.01$, Figure 4). Between ADV and

CONV, a statistically relevant difference was found for L5 (increased translation for ADV, $p_{\text{Wilcoxon}} \leq 0.01$).

[Insert Figure 3 and 4 near here]

3.2 Secondary Outcomes

Participants reported that they sat on both chairs for 3.9 (± 0.8) hours. Analysing the questionnaire on global level revealed a trend ($p=0.03$, $ES=1.23$) that INV was rated substantially better than ADV (Table 2). On a single question level, four questions were identified that support the global level trend: Participants assessed the chair comfort of INV as good (ADV: rather good) and the backrest was not disturbing during active sitting (ADV: rather not disturbing). Compared to subject's own office chairs, INV was rated good and ADV rather good, but 5 out of 8 participants preferred INV for their own office, 3 could not decide (equal rating) and none preferred ADV. Based on sample size calculation, 24 participants should be included in a future long-term field study (Table 2).

[Insert Table 2 near here]

4 Discussion

The primary aim of this study was to analyse the impact of the location of an additional motion axis on upper body stability to analyse the feasibility of using a backrest support during active sitting. Three different principles of dynamic office chairs were included: INV was equipped with an additional motion axis above the seat level, ADV with an additional motion axis below the seat level, and CONV was not equipped with an additional motion axis.

4.1 Primary Outcome

The kinematic analysis highlighted several effects of the motion axis location on upper body stability. Although participants laterally flexed the spine on all chairs in approximately the same range, the thorax and head were almost stable on INV while they were moved two to five times further on the other chairs. Accordingly, the spine angle on INV resulted mainly from the inclination of the pelvis (accounts for 86% of lateral spinal flexion), whereas the spine angle on the other two chairs resulted from a combined pelvis (accounts for ADV: 46% and CONV: 70%) and a counter rotational thorax inclination (accounts for 54% and 30%, Figure 3). Despite the large pelvis inclination for INV, inverting the advanced dynamic chair principle by placing the motion axis above the seat level eliminated lateral pelvis translation. In addition, pelvis inclination showed an opposite motion pattern depending on the motion axis location: On INV, participants inclined the pelvis clockwise (left side up) while moving the seat to the left side, resulting in an inward-directed pelvis inclination (Figure 1). On ADV, participants inclined the pelvis counter-clockwise (left side down) while moving the seat to the left side, resulting in an outward-directed pelvis inclination. Combining these two effects (larger translation and outward-directed inclination), participants had to compensate the large pelvis motion on ADV by tilting the thorax and head back to the middle position. This motion pattern is also evident when looking at the lateral spine translation (Figure 4) for which, in particular in the range of the lumbar backrest support (L3 to T12), an increased vertebral translation was found for ADV. Consequently, upper body stability was significantly reduced and thus the use of a backrest in combination with ADV seems to be severely restricted. In line with Grooten et al. (2013), the missing upper body stability is hypothesized to be the reason why office workers do not use this chair in an active manner during computer based office work.

Although the seat of CONV was not moveable in lateral direction, an ADV-like motion pattern was found for this chair. Participants had to roll the pelvis over the seat to laterally flex the spine, which is why the range of lateral pelvis motion for CONV was between INV and ADV.

In conclusion, the purpose of INV to allow the user to move their spine in the frontal plane while simultaneously holding a stable upper body posture has been confirmed. The results demonstrate why the additional motion axis should be placed above the seat level in order to promote active sitting with backrest support.

4.2 Secondary Outcomes

The analysis of the questionnaire showed several statistical trends that indicate a better rating for INV and thus confirm the kinematic findings. In particular, the overall rating and the comparison to participant's own chairs highlighted the advantages of INV ($p \leq 0.03$, $ES \geq 1.2$). The trend for better ratings of INV's backrest and thus its comfort is in line with the kinematic analysis. The missing upper body stability for ADV is, similar to the conclusion of Grooten et al. 2013, thought to negatively affect the working posture and thus user satisfaction. Therefore, participants preferred to use INV for their own work. However, the results demonstrate that 24 participants should be included in a subsequent field study to analyse whether the chair ratings differ at a 0.01 significance level in the long term.

4.3 Comparison to other Studies

The results of this study are in line with the development study of INV (Kuster et al. 2016). Additional kinematic comparisons to other studies investigating active sitting with a comparable body motion are unfortunately restricted. This study investigates active sitting with pelvis mobilisation, while others investigated active

sitting with thorax mobilisation (e.g. Park and Yoo 2011). For reasons described above, we assume that active sitting with thorax mobilisation makes no sense in office occasions.

Ellegast et al. (2012) observed a lateral trunk inclination during common office tasks between 1.1° and 2.3° (95th Percentiles). Compared to the results of this study, only the thorax inclination of INV (ROM of 1.8°) was within the limit while active sitting on the other chairs resulted in three to five times larger inclinations. Additionally, van Dieën, de Looze, and Hermans (2001) observed that subjects hold the 7th cervical vertebra spontaneously between 50% and 67% of the time within a range of 30 mm around an average position (in sagittal plane) during desk based computer work and classified this time as static. However, the present study demonstrates that by using INV, the 7th cervical vertebra remains within a range of only 10 mm (in frontal plane) even during a lateral spine flexion of more than 10° , while it was moved ≥ 30 mm on the other chairs (Figure 4). The novel office chair might therefore allow for active sitting with a stable upper body posture to use the backrest support during computer based office work.

4.4 Critical Appraisal

Several studies comparing different office chairs and tasks report that the office worker's physical activity level is primarily influenced by the work task and not the chair type (Ellegast et al. 2012; Gregory, Dunk, and Callaghan 2006; Groenesteijn et al. 2012; van Dieën, de Looze, and Hermans 2001). However, the reported seat motions are typically very limited (below 3°) and the chairs differ only slightly in their motion ability (Ellegast et al. 2012; Lengsfeld et al. 2000; Lengsfeld et al. 2007; van Dieën, de Looze, and Hermans 2001). In contrast, the physical demands of the investigated office tasks differ strongly, e.g. sorting documents versus computer based office work

(Ellegast, Keller, and Hamburger 2008; Groenesteijn et al. 2012). It is therefore not surprising that major differences are primarily found with respect to the task. However, for practical reasons it is much easier to change the chair than the task. For this reason, a chair promoting active sitting would be of utmost interest, in particular for computer work that represents the least active office task (Groenesteijn et al. 2012). Since INV follows a completely new approach that enables a stable upper body posture while active sitting and was constructed in a substantially larger ROM ($\pm 13.5^\circ$ and ± 83 mm seat motion), it should be verified in a future field study whether the chair significantly affects the office worker's physical activity level, even in terms of energy expenditure. The authors are aware that the investigated frontal plane motion is so far not commonly performed in daily office. The seats of conventional office chairs do not promote this motion and the study findings provide, in line with the literature, a probable explanation for why office workers do not sit actively on CONV and ADV (missing upper body stability). However, the results of this and the previous study (Kuster et al. 2016) highlight reasons why office workers use INV actively: (1) the upper body remains, in contrast to ADV and CONV, within the limits as observed in office settings and described as stable (Ellegast et al. 2012; van Dieën, de Looze, and Hermans 2001); (2) participants reported that they rather often used the additional frontal plane motion while the backrest was not disturbing; (3) due to the inverse construction of INV (centre of gravity below the motion axis), the office worker sits in a stable position and needs no muscular effort to keep the seat in the middle position which is thought to limit active sitting on ADV (Grooten et al. 2013); (4) the office workers are already familiar with the lateral spine motion from walking (Kuster et al. 2016). Additionally, preliminary results of the subsequent field study indicate that INV approximately doubles the active

sitting time as compared to CONV. However, this particular issue remains a subject of further analyses.

In this study, the upper body kinematics was investigated in one particular computer based office task. Computer work accounts for the largest proportion of time spent in the office, and is known to negatively affect the health of office workers and to be the least active office task (Groenesteijn et al. 2012; IJmker et al. 2007). Studies that investigate different types of computer work like typing, reading or intensive mouse use report no differences in terms of physical activity or upper body kinematics between these activities (Ellegast et al. 2012; Gregory, Dunk, and Callaghan 2006; Groenesteijn et al. 2012). This is why the present study focused on only one particular task for the kinematic analysis, but allowed the participants to perform all kinds of computer tasks during the half working day.

All participants of this study were already familiar with the dynamics of conventional dynamic office chairs and there was no need to include CONV in the familiarization period. Consequently, no comfort and activity ratings were collected for this chair. However, if CONV had been included, participants were likely to have rated their overall experience with CONVs, and not only the half working day. The comparison would therefore be biased by experience (4 hours for INV and ADV versus several years for CONV), which strongly limits the explanatory power of the comparison. We have therefore decided to forego this comparison and accept the limitation. However, we recommend that this comparison is made in a subsequent field study over several weeks. The analysis of the questionnaire revealed no statistically significant difference at the level of 0.01. One might therefore argue that more participants should have been included or the level of significance should have been increased. While the latter would be arbitrary, the sample size of this study was

calculated according to the expected differences of the kinematic motion behaviour. Accordingly, increasing the sample size might have turned non-relevant kinematic differences into significant results. However, the questionnaire was used to verify whether the kinematic findings are in line with the participants' subjective ratings, what they are, and to calculate the required sample size for a subsequent field study.

Finally, it was assumed that a stable thorax and head posture is essential to ensure full concentration on the working task and to enable the use of the backrest during active sitting. Although this is somehow obvious and in line with other studies (Bush and Hubbard 2008; van Dieën, de Looze, and Hermans 2001; Ellegast et al. 2012; Grooten et al. 2017), further research should be done to detect the tolerable ROM limits for upper body kinematics during active sitting with an additional focus on work performance. For the kinematical analysis, the backrests of the chairs had to be removed to ensure marker visibility. Although this sounds counterintuitive when studying the feasibility of active sitting with backrest support, it is the only way to measure upper body stability as well as spinal motion in an accurate way. Another reason to remove the backrests for the kinematic analysis was to ensure independence of seat dynamics and backrest. On INV, there is no need to use the backrest to stabilize the upper body while active sitting. On ADV, the use of the backrest interferes active sitting (the back moves left and right on the backrest). This might explain why our subjects rated the backrest of ADV worse, and is a potential reason why this chair does not promote active sitting (Grooten et al. 2013). In addition, the independence of seat dynamics and backrest ensures that active sitting is not affected if an office worker does not use the backrest. In conclusion, a backless chair that allows for active sitting with such a stable upper body posture, as observed for INV, is very likely to allow also for active sitting with backrest support, which was confirmed by participants chair ratings.

5. Conclusion

This study investigates the impact of the motion axis location for the seat of a dynamic office chair on upper body stability during active sitting. Both the kinematic and questionnaire results demonstrate that placing the motion axis above the seat level allows for active sitting with a stable upper body posture. Thorax and head were shifted by only 11mm and 7mm, respectively, and inclined by less than 2°, while a multiple of this movement was observed for the other chairs. Therefore, in line with the subjective ratings of the participants, we conclude that the backrest can be used even while active sitting. However, whether the new chair promotes active sitting in the long term should be verified in a subsequent field study with at least 24 participants.

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Conflict of Interest

This study was funded by the ZHAW Zurich University of Applied Sciences. No benefits in any form from a commercial party related directly or indirectly to the subject of this study have been or will be received. The investigated chairs were either purchased from an office retailer (ADV and CONV) or provided by the manufacturer free of charge (INV). The study was carried out with permission of ETH Zurich, the owner of the intellectual property rights of the inverted chair principle. One of the authors (DB) is the inventor of the inverted principle and owner of rotavis® who holds the right to commercially use the intellectual property right. However, this has not influenced this study in any form.

Highlights

- We recommend equipping dynamic office chairs with an additional degree of freedom in the frontal plane.
- The additional degree of freedom should have a motion axis above the seat level.
- Participants laterally flexed the spine (12°) while holding a stable upper body position ($\leq 11\text{ mm}$, $\leq 2^\circ$) to focus on computer work.
- The new chair might therefore be suitable for active sitting with backrest support.
- A subsequent field study should include 24 office workers to verify the results for long-term use.

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Table and Figure captions

Table 1. Marker placement according to Plug-in-Gait-Model (Davis et al. 1991; Kadaba, Ramakrishnan, and Wootten 1990) with additional markers placed according to the recommendation of Ernst et al. 2013.

Table 2. Chair ratings for INV (inverted dynamic principle) and ADV (advanced dynamic principle). Indicated is the mean \pm standard deviation (SD), scale from 1 (worst) to 6 (best). Column statistics consists of p-value (Wilcoxon matched-pair test), effect size (ES) according to Cohen (1988, 1992), and required sample size (SS) to reject the hypothesis that the chair ratings are equal at a 0.01 significance level (Faul et al. 2007) for questions with a statistical trend (defined as $p \leq 0.1$ and $ES \geq 0.8$, marked with †).

Figure 1. Motion behaviour on INV (inverted dynamic principle), ADV (advanced dynamic principle), and CONV (conventional dynamic principle). The dark circled cross marks the location of the frontal plane motion axis for INV (above) and ADV (below the seat). The arrow indicates the seat motion around this axis (solid line the seat motion for the indicated lateral flexion, dotted line to the contralateral side). Note that in consequence of the motion axis location, the seats of INV and ADV are moved to opposite directions during lateral spine flexion to the same direction.

Figure 2. Left: Investigated dynamic office chairs (INV: inverted dynamic principle, ADV: advanced dynamic principle, CONV: conventional dynamic principle). Note that all seats were moveable in horizontal and sagittal plane but only frontal plane

motion axes are shown. The backrests were not moveable in frontal plane. Right: Sketch of the laboratory setting, view from top.

Figure 3. Range of motion of lateral inclination/flexion and translation of the investigated body segments for INV (inverted dynamic principle), ADV (advanced dynamic principle), and CONV (conventional dynamic principle). Note that all participants inclined the pelvis in the opposite direction of thorax and head, and that the seat of INV and ADV were moved to opposite directions during lateral flexion to the same direction. The seat of CONV was not moved in lateral direction. Statistical differences marked with asterisks (**: $p \leq .01$ ***: $p \leq .001$).

Figure 4. Range of lateral spine translation for INV (inverted dynamic principle), ADV (advanced dynamic principle), and CONV (conventional dynamic principle). The individual spine markers are located on the vertical axis according to their back position. Statistically significant increased vertebra translation of ADV and CONV compared to INV marked with asterisks (**: $p \leq .01$ ***: $p \leq .001$), statistically significant increased vertebra translation of ADV compared to CONV marked with hash characters (##: $p \leq .01$).

Table 1

Segment	Marker	Placement
Head	LFHD	Left front head, horizontal to RFHD
	RFHD	Right front head, horizontal to LFHD
	LBHD	Left back head, horizontal to RBHD
	RBHD	Right back head, horizontal to LBHD
Thorax	C7 ¹	Spinous process of 7 th cervical vertebra
	T10 ¹	Spinous process of 10 th thoracic vertebra
	CLAV	Centered between articuli sterno-clavicularis
	STRN	Xiphoid process of the sternum
Spine	T2 ²	Spinous process of 2 nd thoracic vertebra
	T4 ²	Spinous process of 4 th thoracic vertebra
	T6 ²	Spinous process of 6 th thoracic vertebra
	T12 ²	Spinous process of 12 th thoracic vertebra
	L1 ²	Spinous process of 1 st lumbar vertebra
	L3 ²	Spinous process of 3 rd lumbar vertebra
	L5 ²	Spinous process of 5 th lumbar vertebra
Pelvis	LPSI	Left posterior superior iliac spine
	RPSI	Right posterior superior iliac spine
	LSID ²	Centred on connecting line between LPSI and LASI ³
	RSID ²	Centred on connecting line between RPSI and RASI ³

- 1) Markers belong to the segments thorax and spine
- 2) Additional markers
- 3) L/RASI = left/right anterior superior iliac spine

Table 2

Question	INV		ERG		statistics		
	Mean	±SD	Mean	±SD	p	ES	SS
overall rating [†]	60.31	±4.91	53.06	±6.71	0.03	1.23	n = 20
design	4.13	±0.99	4.25	±0.71	1.00	0.15	
chair comfort [†]	5.25	±0.71	4.13	±1.25	0.08	1.11	n = 23
backrest comfort [†]	5.34	±0.74	4.22	±1.26	0.08	1.09	n = 24
seat comfort	5.00	±0.76	4.25	±1.28	0.29	0.71	
chair dynamics	4.75	±0.71	4.38	±1.06	0.74	0.42	
seat dynamics	5.13	±0.64	4.88	±0.83	0.73	0.34	
movement perception	5.06	±0.78	4.97	±1.20	1.00	0.09	
movement execution	4.13	±0.83	3.75	±1.16	0.42	0.37	
work influence	3.60	±0.64	3.00	±0.64	0.19	0.94	
effect on performance	4.05	±0.62	3.68	±0.81	0.45	0.52	
safety	4.75	±1.04	4.75	±1.04	1.00	0.00	
well-being	4.88	±1.06	4.13	±2.23	0.76	0.43	
chair comparison [†]	5.00	±0.53	3.88	±0.83	0.02	1.61	n = 13
everyday use [†]	5.63	±0.52	4.38	±1.51	0.10	1.11	n = 23

Figure 1

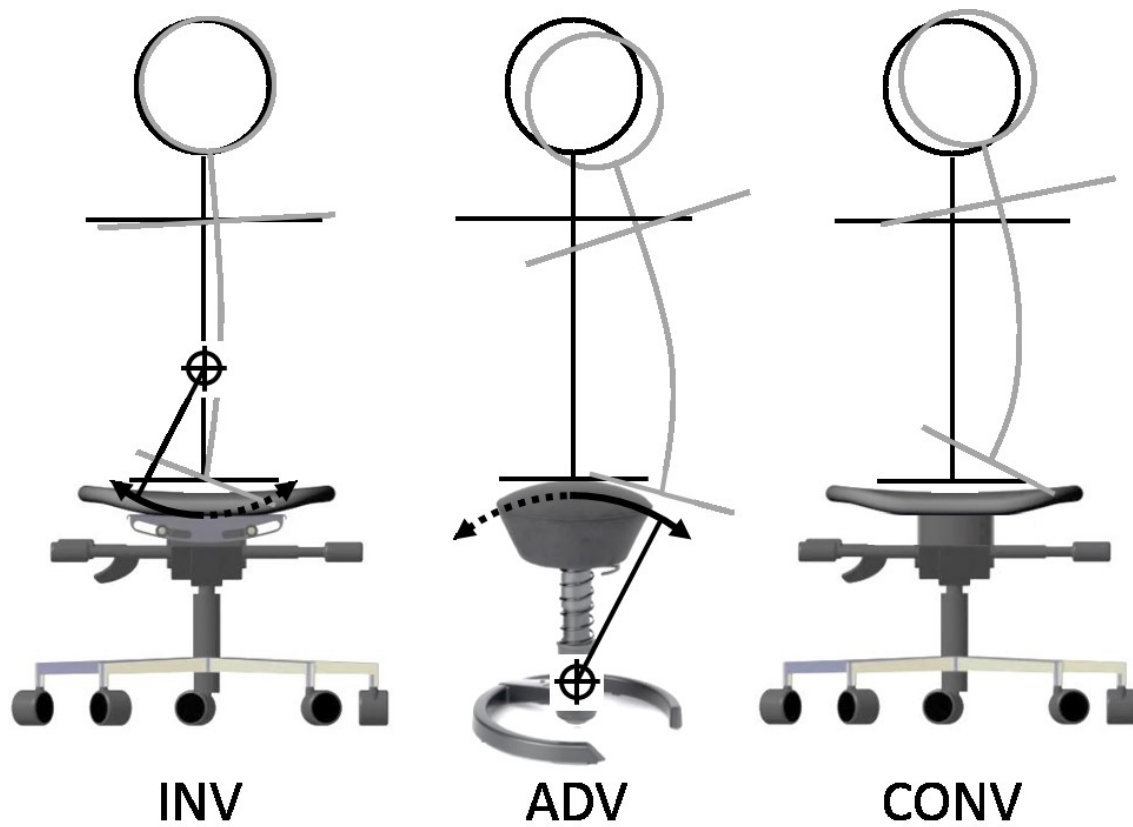


Figure 2



Figure 3

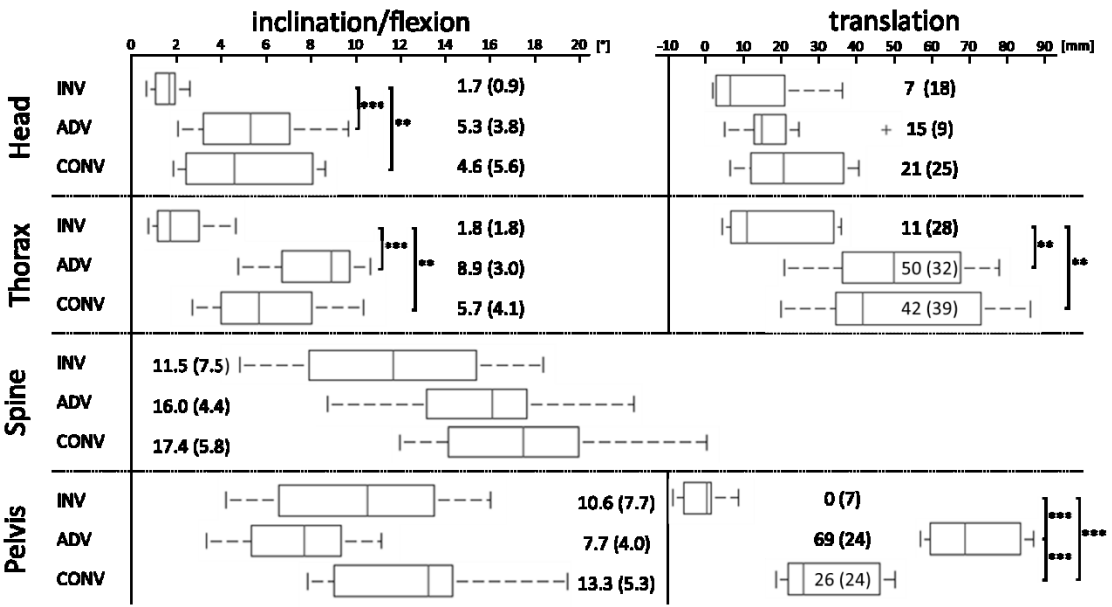
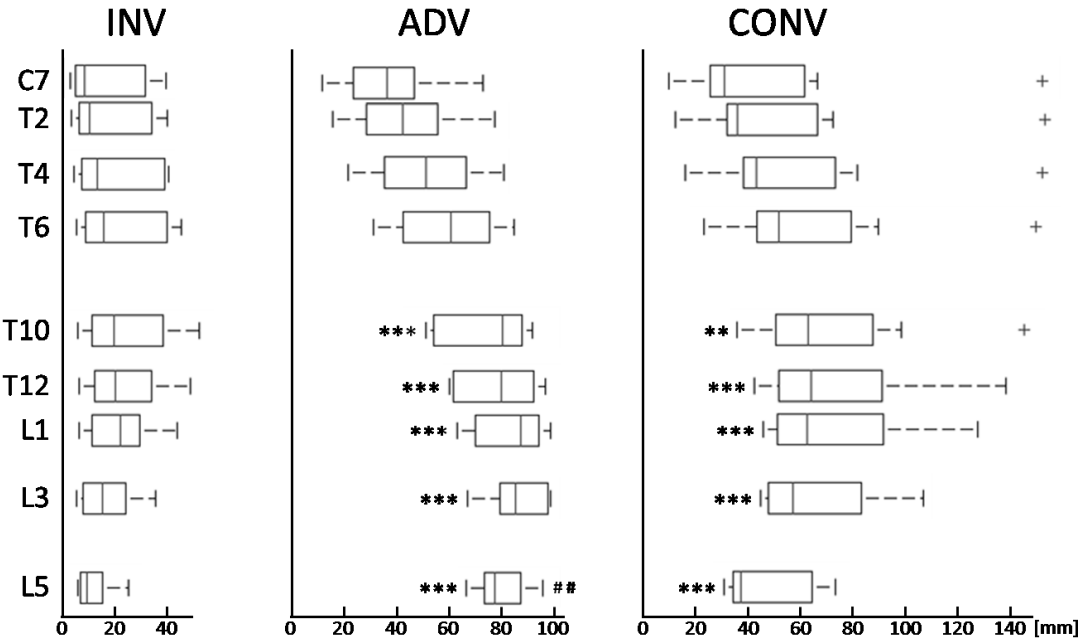


Figure 4



Appendix

Table A1: The questionnaire is based on the study of Groenesteijn et al. 2012, except questions g, j, and n that were added for this study. Response options were numbered according to the order listed from 1 (worst) to 6 (best). Due to the inverse formulation of question g, response options were numbered in reverse order. Note that participants filled out the questionnaire in German.

a) design:	Do you like the design of the chair? No, not at all – No – Rather no – Rather yes – Yes – Yes, very much
b) chair comfort:	How do you assess the comfort of this chair? Very bad – Bad – Rather bad – Rather good – Good – Very good
c) movement perception:	To what extent did you perceived the mobility of the seat? Not at all – Almost not – Little – Rather obvious – Obvious – Very obvious
d) seat dynamics:	How do you like the mobility of the seat? Very bad – Bad – Rather bad – Rather good – Good – Very good
e) seat comfort:	How do you rate the overall comfort of the seat? Very bad – Bad – Rather bad – Rather good – Good – Very good
f) chair dynamics:	How do you like the overall dynamics and mobility of the chair? Very bad – Bad – Rather bad – Rather good – Good – Very good
g) backrest comfort:	Does the backrest disturb you during dynamic movement? No, not at all – No – Rather no – Rather yes – Yes – Yes, very much
h) work influence:	To what extent were your working activities influenced by the dynamics and mobility of the chair? Very negative – Negative – Rather negative – Rather positive – Positive – Very positive
j) movement execution:	How often have you consciously performed the additional movement? Very rarely – Rarely – Rather rarely – Rather often – Often – Very often
k) safety:	How safe do you feel on this chair? Very unsafe – Unsafe – Rather unsafe – Rather safe – Safe – Very safe
l) well-being:	Does this chair assist your physical well-being? No, not at all – No – Rather no – Rather yes – Yes – Yes, very much
m) effect on performance:	In your opinion, what is the influence this chair would have on your work performance? Very negative – Negative – Rather negative – Rather positive – Positive – Very positive
n) chair comparison:	How do you rate this chair compared to your own office chair? Very bad – Bad – Rather bad – Rather good – Good – Very good
o) everyday use:	To what extent would you like to have this chair as your office chair? Strongly unwilling – Unwilling – Rather unwilling – Rather willing – Willing – Strongly willing